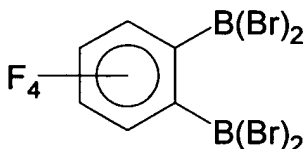


POLYMERIZATION OF I-BUTENE IN HYDROCARBON MEDIA USING BIS(BORANE) CO-INITIATORS

TECHNICAL FIELD

This invention relates to a cationic-polymerization method that uses new coinitiators.

This invention also relates to a method for synthesizing $1,2\text{-C}_6\text{F}_4[\text{B}(\text{Br})_2]_2$:



BACKGROUND OF THE INVENTION

Poly(isobutene) (PIB) is an important industrial commodity that is prepared by the polymerization of isobutene (IB), a cheap petrochemical obtained by the cracking of higher hydrocarbons. Depending on its molecular weight (MW), PIB is used in hundreds if not thousands of diverse applications, e.g., rubbers, lubricants, adhesives, viscosity control agents, additives. The polymerization of IB is carried out by large companies world-wide, including Exxon-Mobil, BASF, Oronite, BP, Japan Synthetic Rubber, etc.

IB polymerization is effected either in the bulk (BASF) or in the liquid phase by the use of hydrocarbon or chlorinated hydrocarbon diluents at cryogenic temperatures. The typical polymerization initiation systems include strong Lewis acids (BF_3 , AlCl_3 , TiCl_4 , etc); these acids are highly moisture sensitive and rapidly hydrolyze to noxious side products during work-up. Environmental concerns (air, water pollution) present important issues even with state-of-the-art industrial processes.

Cationically polymerized olefins, such as butyl rubber, a co-polymer of i-butene (IB) and isoprene (IP), have long been commercially important synthetic rubbers. For example, about 500 million pounds of butyl rubber (BR) were produced in the United States in 1991. Conventional methods of BR manufacture employ low temperature (as low as -100°C) and the presence of a Lewis acid, such as AlCl_3 , in a chlorinated hydrocarbon solvent. Under these conditions, production of high

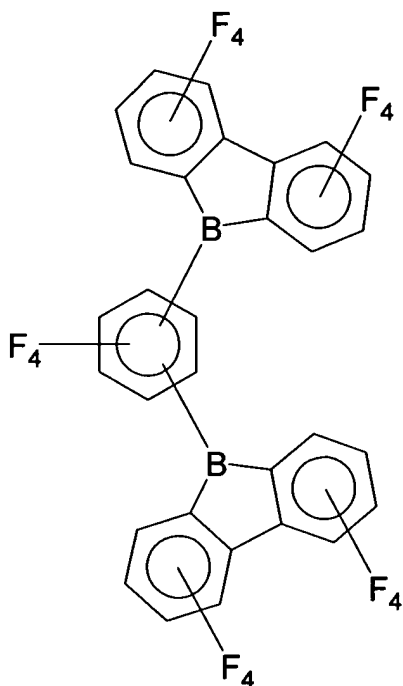
MW (> 200,000) BR, occurs at acceptable rates. Chlorinated hydrocarbon solvents are used because they have sufficient polarity to stabilize the transition states, and thus lower the activation energy for ion generation in carbocationic polymerization. The low temperatures are used to slow the termination and chain transfer processes that limit the growth in the molecular weight of the polymer chains. Less polar solvents are generally less effective at stabilizing transition states, and thus fewer carbocations are produced that are active in polymerization. The solvent also needs to act as a fluid heat transfer medium to dissipate the heat of polymerization. The solvent should optimally dissolve the ingredients of the polymerization. Methyl chloride is useful in the synthesis of BR, as it is both a polar solvent (which enhances propagation rates) and a poor solvent for BR so that the process is a suspension polymerization at these low temperatures.

Recent legislation in the United States allows the continued use of methyl chloride in existing facilities, but expanded facilities and/or new plants will be required to use alternative solvents that are not chlorinated. Hence there is a need to develop initiators which will be effective in the absence of a halogenated solvent in producing high MW BR at commercially acceptable rates.

A variety of Lewis acidic, main group and transition metal initiators or co-initiators of i-butene (IB) polymerization have been reported to provide poly(i-butene) (PIB) or co-polymers of IB and IP in the absence of chlorinated solvents or with a minimum amount of chlorinated solvents being present. However, none of these compositions is believed to provide BR of sufficiently high MW at acceptable rates in the absence of chlorinated solvents. Therefore, there is a continuing need to develop alternative initiator compositions.

SUMMARY OF INVENTION

This invention is generally directed to a method for cationically polymerizing olefin monomer comprising the step of using a composition having the chemical structure:



as a coinitiator in the presence of water.

This invention is generally directed to a method for cationically polymerizing olefin monomer comprising the step of using a composition having the chemical structure:



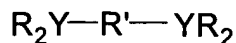
as a coinitiator in the presence of water;

wherein each R is independently selected from the group consisting of a perfluorophenyl; 3,5-bis(trifluoromethyl)phenyl; 1-perfluoronaphthyl; 2-perfluoronaphthyl; 2-perfluorobiphenyl; 3-perfluorobiphenyl; 4-perfluorobiphenyl; and $p-R''_3Si$ -2,3,5,6-tetrafluorophenyl;

wherein R' is 1,2-perfluorophenylenyl; 1,2-perfluoronaphthalenyl; 2,3-perfluoronaphthalenyl; 1,8-perfluoronaphthalenyl; 1,2-perfluoroanthracenyl; 2,3-perfluoroanthracenyl; 1,9-perfluoroanthracenyl; 1,2-perfluorophenanthrenyl; 2,3-perfluorophenanthrenyl; 1,10-perfluorophenanthrenyl; 9,10-perfluorophenanthrenyl; 2,2'-perfluorobiphenylenyl; 2,2'-perfluoro-1,1'-binaphthalenyl; 3,3'-perfluoro-2,2'-binaphthalenyl; or 1,1'-ferrocenyl; and

wherein R'' is a C₁, C₂, C₃, C₄, C₅, C₆, C₇, C₈, C₉, or C₁₀ alkyl.

This invention is generally directed to a method for cationically polymerizing olefin monomer comprising the step of using a composition having the chemical structure:



as a coinitiator in an organic phase or neat monomer reaction phase;

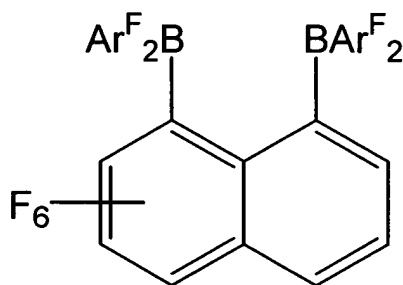
wherein Y is boron or aluminum;

wherein each R is independently selected from the group consisting of a perfluorophenyl; 3,5-bis(trifluoromethyl)phenyl; 1-perfluoronaphthyl; 2-perfluoronaphthyl; 2-perfluorobiphenyl; 3-perfluorobiphenyl; 4-perfluorobiphenyl; and *p*-R''₃Si-2,3,5,6-tetrafluorophenyl;

wherein R' is 1,2-perfluorophenylenyl; 1,2-perfluoronaphthalenyl; 2,3-perfluoronaphthalenyl; 1,8-perfluoronaphthalenyl; 1,2-perfluoroanthracenyl; 2,3-perfluoroanthracenyl; 1,9-perfluoroanthracenyl; 1,2-perfluorophenanthrenyl; 2,3-perfluorophenanthrenyl; 1,10-perfluorophenanthrenyl; 9,10-perfluorophenanthrenyl; 2,2'-perfluorobiphenylenyl; 2,2'-perfluoro-1,1'-binaphthalenyl; 3,3'-perfluoro-2,2'-binaphthalenyl; or 1,1'-ferrocenyl; and

wherein R'' is a C₁, C₂, C₃, C₄, C₅, C₆, C₇, C₈, C₉, or C₁₀ alkyl.

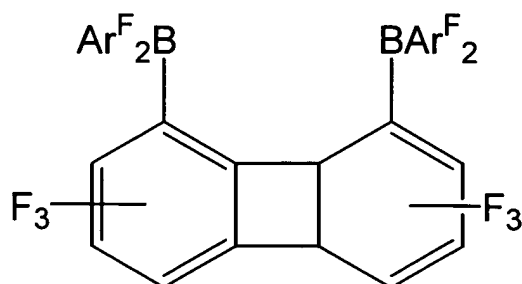
This invention is generally directed to a method for cationically polymerizing olefin monomers comprising the step of using a composition having the chemical structure:



wherein $Ar^F = C_6F_5$ or $Ar^F_2 = C_{12}F_8$

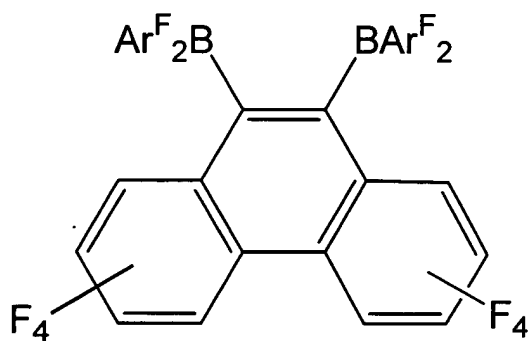
as a coinitiator in the presence of water.

This invention is generally directed to a method for cationically polymerizing olefin monomers comprising the step of using a composition having the chemical structure:



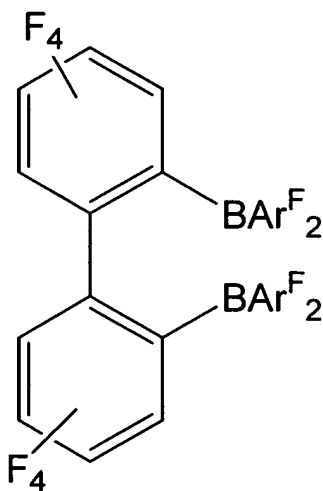
wherein $\text{Ar}^{\text{F}} = \text{C}_6\text{F}_5$ or $\text{Ar}^{\text{F}}_2 = \text{C}_{12}\text{F}_8$
as a coinitiator in the presence of water.

15 This invention is generally directed to a method for cationically polymerizing olefin monomers comprising the step of using a composition having the chemical structure:



wherein $\text{Ar}^{\text{F}} = \text{C}_6\text{F}_5$ or $\text{Ar}^{\text{F}}_2 = \text{C}_{12}\text{F}_8$

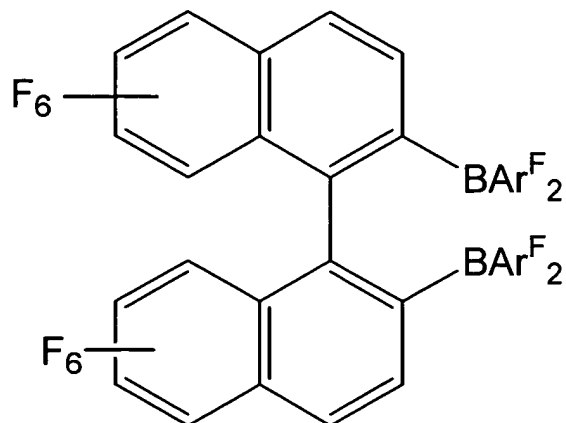
This invention is generally directed to a method for cationically polymerizing olefin monomers comprising the step of using a composition having the chemical structure:



wherein $\text{Ar}^{\text{F}} = \text{C}_6\text{F}_5$ or $\text{Ar}^{\text{F}}_2 = \text{C}_{12}\text{F}_8$

as a coinitiator in the presence of water.

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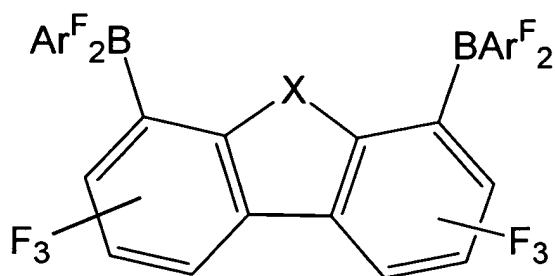


wherein

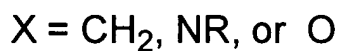


as a coinitiator in the presence of water.

This invention is generally directed to a method for cationically polymerizing olefin monomers comprising the step of using a composition having the chemical structure:



wherein

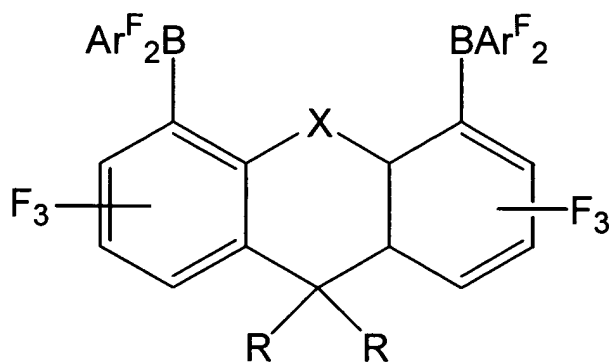


and



as a coinitiator in the presence of water.

This invention is generally directed to a method for cationically polymerizing olefin monomers comprising the step of using a composition having the chemical structure:



wherein

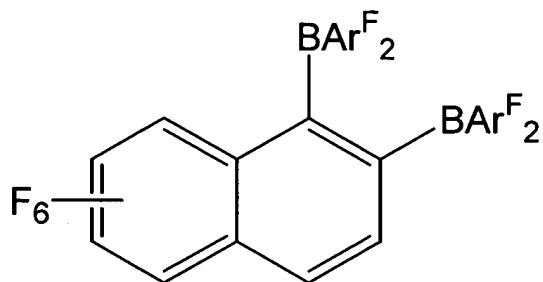
$X = \text{CH}_2, \text{NR}, \text{ or O}$

and

$\text{Ar}^F = \text{C}_6\text{F}_5 \text{ or } \text{Ar}^F_2 = \text{C}_{12}\text{F}_8$

as a coinitiator in the presence of water.

This invention is generally directed to a method for cationically polymerizing olefin monomers comprising the step of using a composition having the chemical structure:

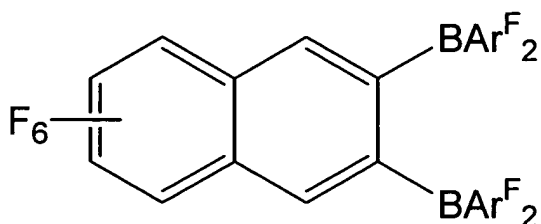


wherein

$\text{Ar}^F = \text{C}_6\text{F}_5 \text{ or } \text{Ar}^F_2 = \text{C}_{12}\text{F}_8$

as a coinitiator in the presence of water.

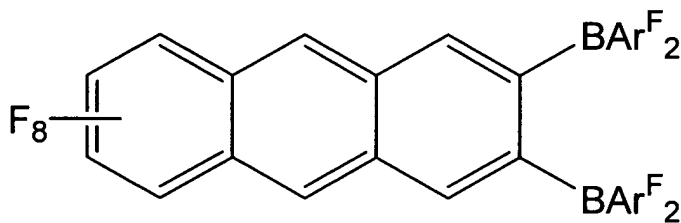
This invention is generally directed to a method for cationically polymerizing olefin monomers comprising the step of using a composition having the chemical structure:



10 wherein $Ar^F = C_6F_5$ or $Ar^F_2 = C_{12}F_8$

as a coinitiator in the presence of water.

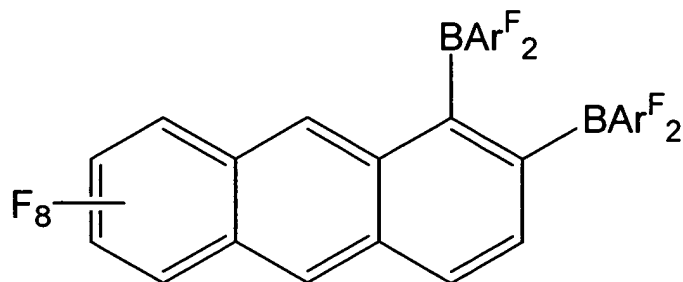
This invention is generally directed to a method for cationically polymerizing olefin monomers comprising the step of using a composition having the chemical structure:



25 wherein $Ar^F = C_6F_5$ or $Ar^F_2 = C_{12}F_8$

as a coinitiator in the presence of water.

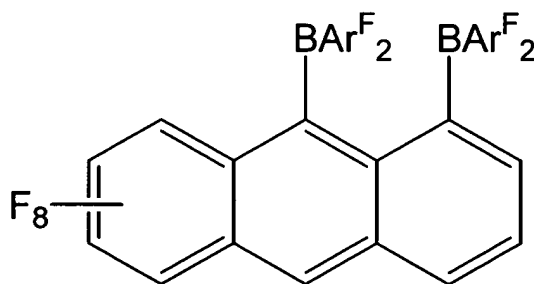
This invention is generally directed to a method for cationically polymerizing olefin monomers comprising the step of using a composition having the chemical structure:



wherein $\text{Ar}^{\text{F}} = \text{C}_6\text{F}_5$ or $\text{Ar}^{\text{F}}_2 = \text{C}_{12}\text{F}_8$

as a coinitiator in the presence of water.

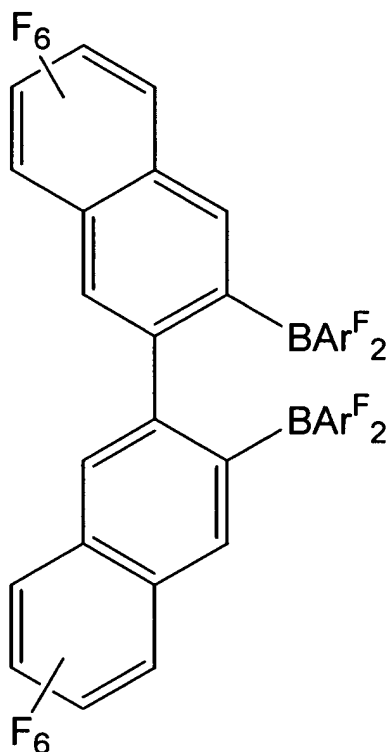
This invention is generally directed to a method for cationically polymerizing olefin monomers comprising the step of using a composition having the chemical structure:



wherein $\text{Ar}^{\text{F}} = \text{C}_6\text{F}_5$ or $\text{Ar}^{\text{F}}_2 = \text{C}_{12}\text{F}_8$

as a coinitiator in the presence of water.

This invention is generally directed to a method for cationically polymerizing olefin monomers comprising the step of using a composition having the chemical structure:

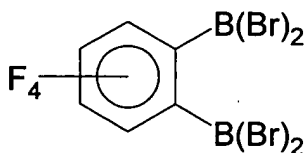


wherein



as a coinitiator in the presence of water.

This invention generally provides a cationic-polymerization method that uses new coinitiators. The invention also provides for a cationic-polymerization method that uses new coinitiators in the presence of water. This invention also provides a method for making 1,2- $\text{C}_6\text{F}_4[\text{B}(\text{Br})_2]_2$:



at an improved yield compared to prior-art methods.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1 is the chemical structure of 1,2-bis(9-bora-1,2,3,4,5,6,7,8-octafluorofluorenyl)-3,4,5,6-tetrafluorobenzene;

FIGURE 2 is a schematic illustration of a representative method of the invention for synthesizing 1,2-bis(9-bora-1,2,3,4,5,6,7,8-octafluorofluorenyl)-3,4,5,6-tetrafluorobenzene;

FIGURE 3 is a schematic illustration of the chemical structure of a representative compound of the invention, a 1,8-bis(BAr^F₂)hexafluoronaphthalene compound;

FIGURE 4 is a schematic illustration of the chemical structure of a representative compound of the invention, a 1,8-bis(BAr^F₂)hexafluorobiphenylene compound;

FIGURE 5 is a schematic illustration of the chemical structure of a representative compound of the invention, a 9,10-bis(BAr^F₂)octafluorophenanthrene compound;

FIGURE 6 is a schematic illustration of the chemical structure of a representative compound of the invention, a 2,2'-bis(BAr^F₂)octafluorobiphenyl compound;

FIGURE 7 is a schematic illustration of the chemical structure of a representative compound of the invention, a 2,2'-bis(BAr^F₂)dodecafluoro-1,1'-binaphthalene compound;

FIGURE 8 is a schematic illustration of the chemical structure of representative compounds of the invention; a 1,8-bis(BAr^F₂)hexafluorofluorene compound when X = CH₂; a 1,8-bis(BAr^F₂)hexafluorocarbazole compound when X = NR; and a 1,8-bis(BAr^F₂)hexafluorodibenzofuran compound when X = O;

FIGURE 9 is a schematic illustration of the chemical structure of representative dihydroanthracene compounds of the invention; a 1,8-bis(BAr^F₂)-10,10-disubstituted-hexafluorodihydroanthracene compound when X = CH₂; a 1,8-bis(BAr^F₂)-10,10-disubstituted-9-

aza-hexafluorodihydroanthracene compound when $X = \text{NR}$; and a 1,8-bis(BAr^{F}_2)-10,10-disubstituted-9-oxo-hexafluorodihydroanthracene compound when $X = \text{O}$;

FIGURE 10 is a schematic illustration of the chemical structure of a representative compound of the invention, a 1,2-bis(BAr^{F}_2)hexafluoronaphthalene compound;

FIGURE 11 is a schematic illustration of the chemical structure of a representative compound of the invention, a 2,3-bis(BAr^{F}_2)hexafluoronaphthalene compound;

FIGURE 12 is a schematic illustration of the chemical structure of a representative compound of the invention, a 2,3-bis(BAr^{F}_2)octafluoroanthracene compound;

FIGURE 13 is a schematic illustration of the chemical structure of a representative compound of the invention, a 1,2-bis(BAr^{F}_2)octafluoroanthracene compound;

FIGURE 14 is a schematic illustration of the chemical structure of a representative compound of the invention, a 1,9-bis(BAr^{F}_2)octafluoroanthracene compound; and

FIGURE 15 is a schematic illustration of the chemical structure of a representative compound of the invention, a 3,3'-bis(BAr^{F}_2)dodecafluoro-2,2'-binaphthalene compound.

DETAILED DESCRIPTION OF THE INVENTION

This invention generally provides a cationic-polymerization method that uses new coinitiators.

The following compounds can be used as cationic-polymerization coinitiators in the presence of water.

1)



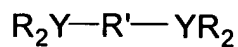
wherein each R is independently selected from the group consisting of a perfluorophenyl; 3,5-bis(trifluoromethyl)phenyl; 1-perfluoronaphthyl; 2-perfluoronaphthyl; 2-perfluorobiphenyl; 3-perfluorobiphenyl; 4-perfluorobiphenyl; and $p\text{-R}''_3\text{Si-2,3,5,6-tetrafluoro-phenyl}$;

wherein R' is 1,2-perfluorophenylene; 1,2-perfluoronaphthalene; 2,3-perfluoronaphthalene; 1,8-perfluoronaphthalene; 1,2-perfluoroanthracene; 2,3-

perfluoroanthracenyl; 1,9-perfluoroanthracenyl; 1,2-perfluorophenanthrenyl; 2,3-perfluorophenanthrenyl; 1,10-perfluorophenanthrenyl; 9,10-perfluorophenanthrenyl; 2,2'-perfluorobiphenylenyl; 2,2'-perfluoro-1,1'-binaphthalenyl; 3,3'-perfluoro-2,2'-binaphthalenyl; or 1,1'-ferrocenyl; and

wherein R'' is a C₁, C₂, C₃, C₄, C₅, C₆, C₇, C₈, C₉, or C₁₀ alkyl.

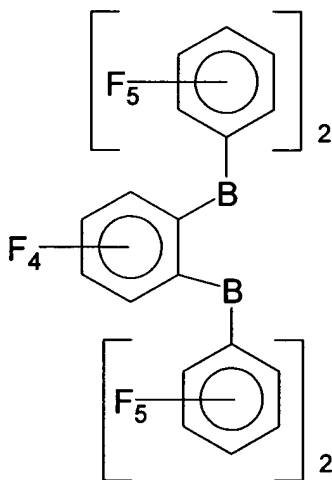
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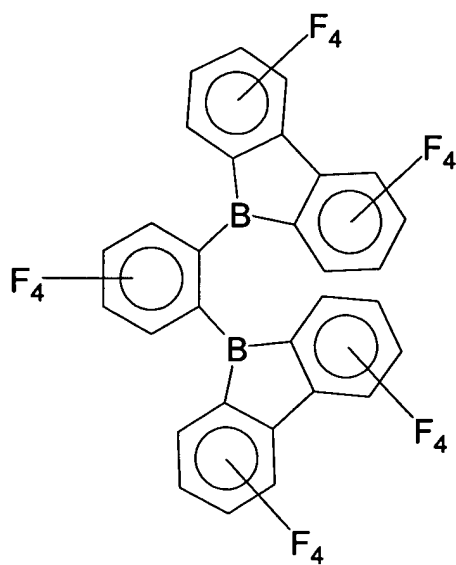
wherein Y is boron or aluminum;

wherein R, R', and R'' is as described above.

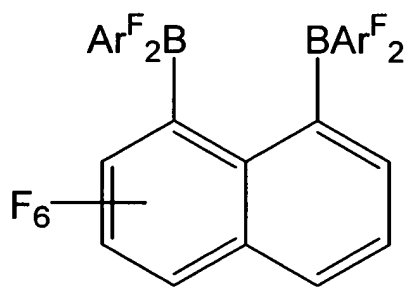
3)



4)



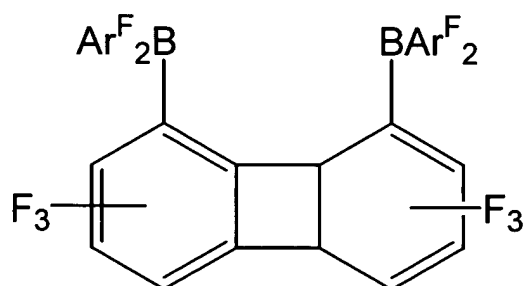
5)



wherein

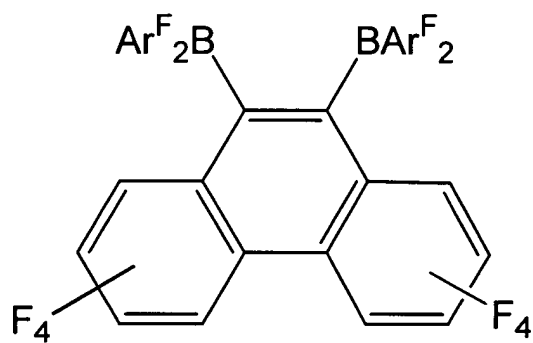


6)



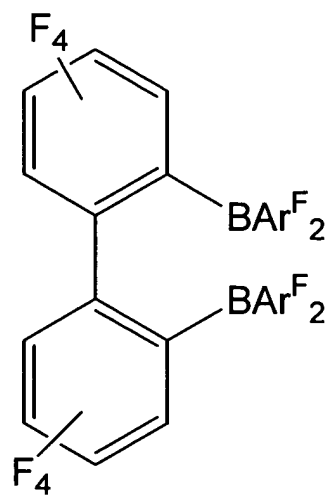
wherein $\text{Ar}^{\text{F}} = \text{C}_6\text{F}_5$ or $\text{Ar}^{\text{F}}_2 = \text{C}_{12}\text{F}_8$

7)

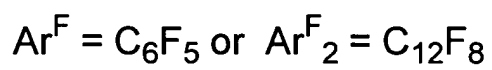


wherein $\text{Ar}^{\text{F}} = \text{C}_6\text{F}_5$ or $\text{Ar}^{\text{F}}_2 = \text{C}_{12}\text{F}_8$

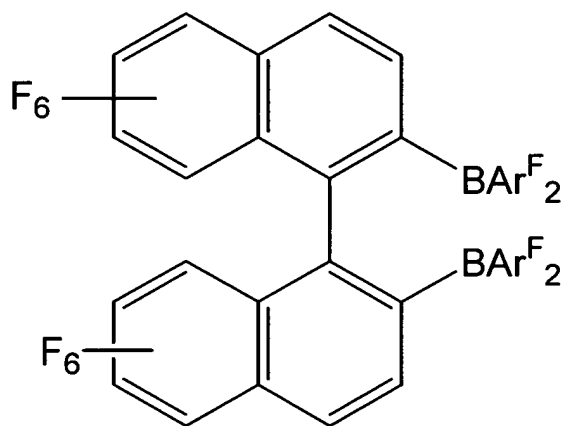
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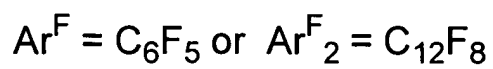
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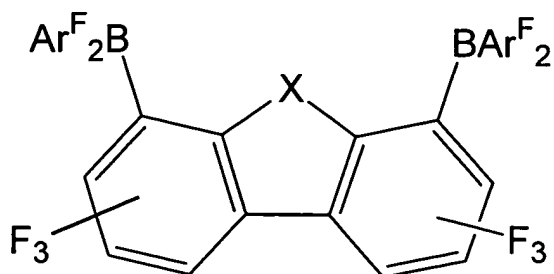
9)



wherein



10)



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wherein

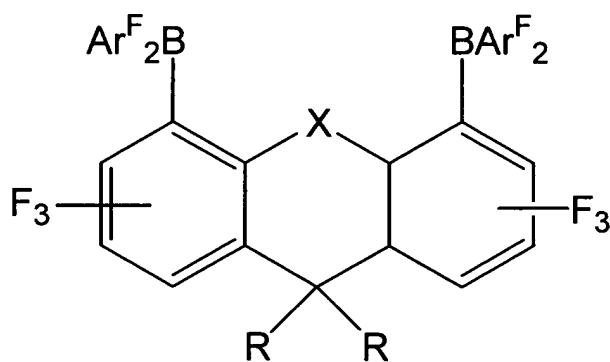
 $X = \text{CH}_2, \text{NR}, \text{ or } \text{O}$

and

 $\text{Ar}^{\text{F}} = \text{C}_6\text{F}_5 \text{ or } \text{Ar}^{\text{F}}_2 = \text{C}_{12}\text{F}_8$

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11)



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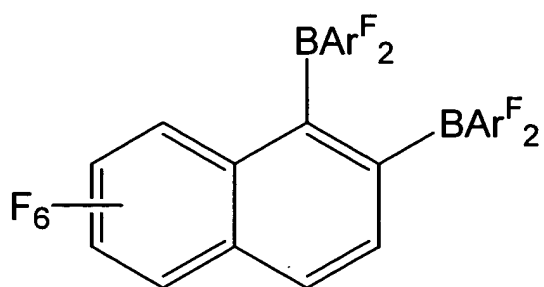
wherein

 $X = \text{CH}_2, \text{NR}, \text{ or } \text{O}$

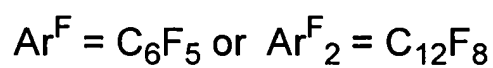
and

 $\text{Ar}^{\text{F}} = \text{C}_6\text{F}_5 \text{ or } \text{Ar}^{\text{F}}_2 = \text{C}_{12}\text{F}_8$

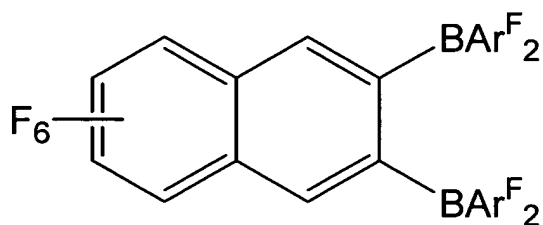
12)



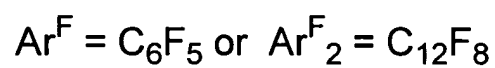
wherein



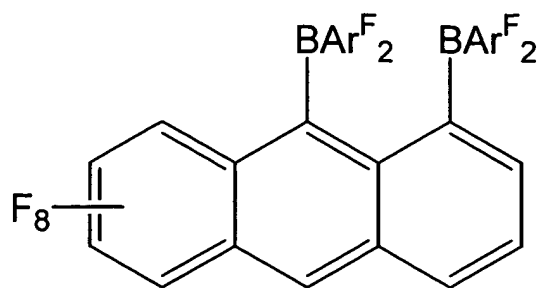
13)



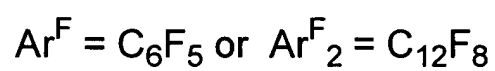
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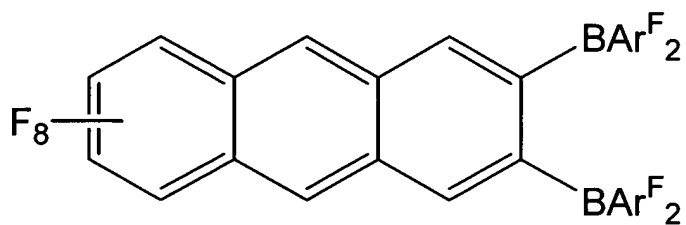
14)



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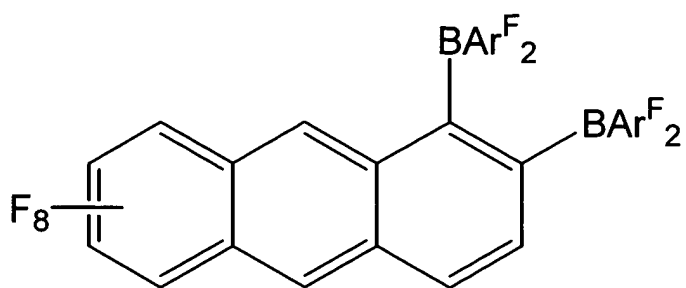
15)



wherein



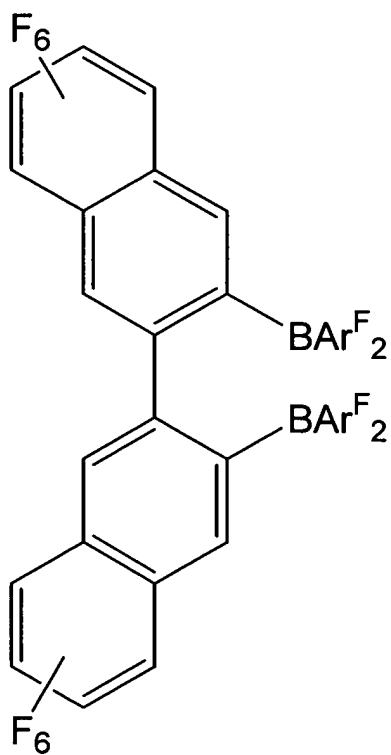
16)



wherein



17)



wherein

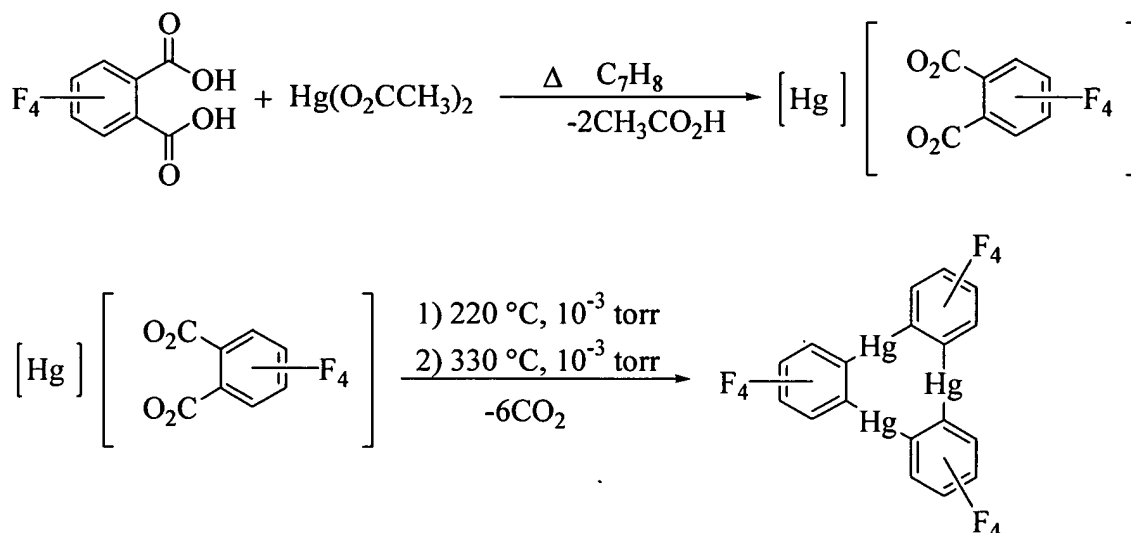


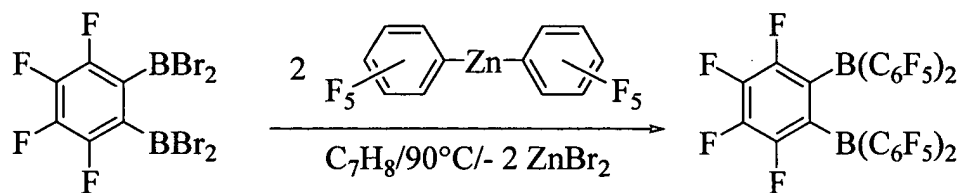
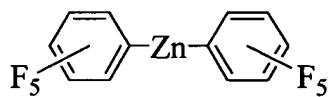
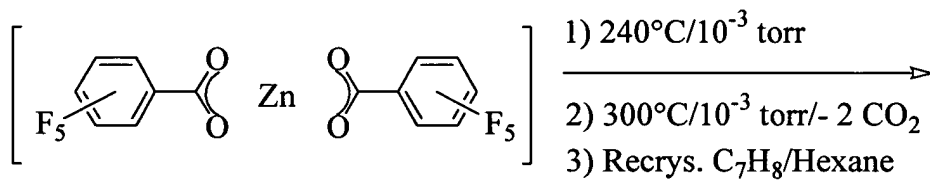
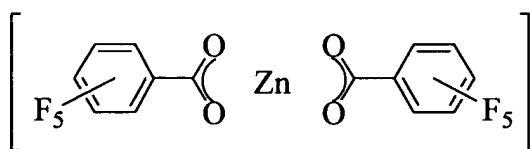
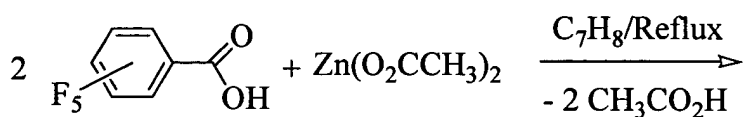
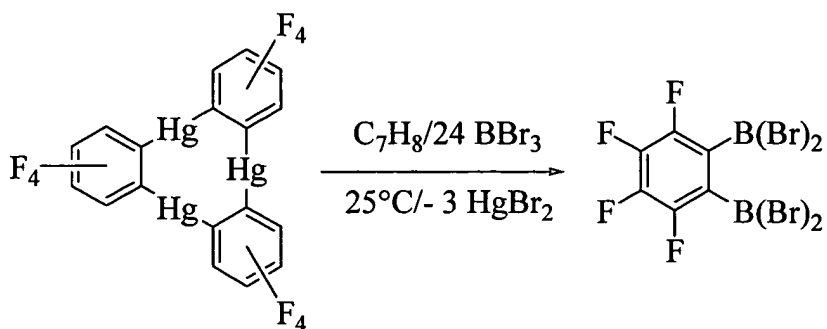
There is no limitation on the cationically polymerizable olefin that can be used. In one embodiment, the olefin monomer(s) selected from C₂-C₃₀ olefins, C₂-C₃₀ diolefins, especially C₂-C₂₀ olefins. Representative examples of olefins that may be polymerized using the initiator of the present invention include ethylene, propylene, butene, pentene, hexene, heptene, octene, nonene, decene, dodecene, dodecyldocene, 3-methyl pentene, 3, 5, 5-trimethyl-hexene, isobutylene, 2-methyl-butene, 2-methyl-pentene, vinyl ether, vinyl carbazole and mixtures thereof. Diolefins may also be included. In one particular example, a mixture of isobutylene (i-butene) and about 0.5 to about 5 percent isoprene is cationically polymerized using the initiator of the present invention to produce butyl rubber. In another example, butyl rubber is produced by cationically polymerizing a mixture of isobutylene (i-butene) and about 0.5 to about 2.5 percent isoprene using the initiator of the present invention.

When the coinitiator is used in the presence of water, in one embodiment it is used in aqueous suspension. In another embodiment, the coinitiator is used an aqueous emulsion polymerization process.

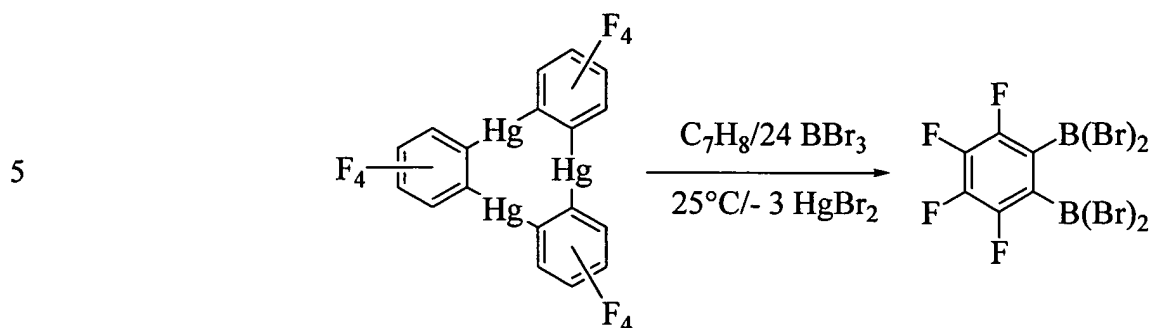
Useful amounts of the coinitiator can be determined by one having ordinary skill in the art without undue experimentation.

The present invention also provides a method of cationically polymerizing at least one cationically polymerizable olefin using an initiating system that includes 1,2-C₆F₄[B(C₆F₅)₂]₂ (1-F₄). 1-F₄ may be synthesized according to the following scheme:





Preferably, the following reaction step:



is preferred at a temperature of less than about 25°C. In another embodiment, the reaction is conducted at a temperature of less than about 35°C.

A schematic illustration of the syntheses of Compounds I and II is shown in FIGURE 2.

Referring to FIGURE 2, the synthetic route starts with tetrafluorodibromobenzene, which was converted to *bis*-boronic acid 1. The *bis*-boronic acid 1 was formed in good yield (75%) and then converted to the dipotassium salt of *bis*-trifluoroborate 2. Sequential treatment with boron trifluoride (BF₃) and then boron tribromide (BBr₃) converted *bis*-trifluoroborate 2 into *bis*-dibromoboryl compound 4, from which both Compounds I and II were prepared. Thus, the preparation of *bis*-dibromoboryl compound 4 constitutes a formal synthesis of Compounds I and II. The synthesis of Compound 1 is described in Example 1. The synthesis of Compound II is described in Example 2.

Thus, a method for making 1,2-bis(9-bora-1,2,3,4,5,6,7,8-octafluorofluorenyl)-3,4,5,6-tetrafluorobenzene (Compound I) is provided. In one embodiment, the synthetic method includes the following steps:

- (a) reacting a 1,2-salt of 3,4,5,6-tetrafluorobenzene with a trialkylborate to provide a bis-boronic acid ester and hydrolyzing the bis-boronic acid ester to provide 1,2-bis[(dihydroxy)boryl]tetrafluorobenzene;
- (b) reacting 1,2-bis[(dihydroxy)boryl]tetrafluorobenzene with a hydrogen difluoride salt to provide a tetrafluorophenyl-bis-1,2-trifluoroborate salt;
- (c) reacting a tetrafluorophenyl-bis-1,2-trifluoroborate salt with boron trifluoride to provide 1,2-bis(difluoroboryl)tetrafluorobenzene;
- (d) reacting 1,2-bis(difluoroboryl)tetrafluorobenzene with boron tribromide to provide 1,2-

bis(dibromoboryl)tetrafluorobenzene; and

- (e) reacting 1,2-bis(dibromoboryl)tetrafluorobenzene with a 9-(dialkyltin) perfluorofluorene to provide 1,2-bis(9-bora-1,2,3,4,5,6,7,8-octafluorofluorenyl)-3,4,5,6-tetrafluorobenzene.

5 A method for making 1,2-bis[di(perfluorophenyl)boryl]-3,4,5,6-tetrafluorobenzene (Compound II) is also provided. In one embodiment, the method includes steps (a) through (d) above followed by reacting 1,2-bis(dibromoboryl)tetrafluorobenzene with di(perfluorophenyl)zinc, $\text{Zn}(\text{C}_6\text{F}_5)_2$, to provide 1,2-bis[di(perfluorophenyl)boryl]-3,4,5,6-tetrafluorobenzene.

10 In one embodiment of the above synthetic methods, the 1,2 salt of 3,4,5,6-tetrafluorobenzene is a 1,2-dilithium salt. In one embodiment, the 1,2-dilithium salt is made by reacting 1,2-dibromo-3,4,5,6-tetrafluorobenzene with n-butyl lithium.

In one embodiment of the above synthetic methods, the trialkylborate is trimethylborate. Suitable alkyl groups include any alkyl group that permits the reaction to proceed efficiently under convenient reaction conditions. Examples of suitable alkyl groups include C1-C12 alkyl groups.

15 In one embodiment of the above synthetic methods, the hydrogen difluoride salt is potassium hydrogen difluoride.

In one embodiment of the above synthetic methods, the tetrafluorophenyl-bis-1,2-trifluoroborate salt is potassium tetrafluorophenyl-bis-1,2-trifluoroborate.

20 In one embodiment of the method for making 1,2-[$\text{B}(\text{C}_{12}\text{F}_8)$] $_2\text{C}_6\text{F}_4$, the 9-(dialkyltin) perfluorofluorene is 9-(dimethyltin) perfluorofluorene. In another embodiment, the 9-(dialkyltin) perfluorofluorene is 9-(dibutyltin) perfluorofluorene.

25 Additionally, analogs of Compound I and Compound II, and methods for making the analogs are provided. Compounds I and II are 1,2-phenyl substituted compounds. Compound I includes a 1,2-phenyl "backbone" structure to which are covalently coupled two 9-bora-perfluorofluorenyl (i.e., $-\text{B}(\text{C}_{12}\text{F}_8)$) substituents. Similarly, Compound II includes a 1,2-phenyl "backbone" structure to which are covalently coupled two boryl di(perfluorophenyl) (i.e., $-\text{B}(\text{C}_6\text{F}_5)_2$) substituents. In addition to compounds having 1,2-phenyl backbone structures, the present invention provides compounds having other backbone structures. Representative backbone structures other than 1,2-phenyl backbone structures are illustrated in FIGURES 3-15. In FIGURES 3-15, Ar^{F} represents

a perfluoroaryl group. In these figures, the perfluoroaryl groups are represented as either Ar^{F} is C_6F_5 (monovalent perfluorophenyl) or Ar^{F_2} is C_{12}F_8 (divalent perfluorofluorene). It will be appreciated that other perfluoroaryl groups are within the scope of the invention.

In one or more embodiments of this invention, the coinitiator compounds are aryl compounds that bear two boron centers directly bonded to a carbon atom of an aromatic ring of the aryl compound. As illustrated in FIGURES 1 and 3-15, the boron centers can be bonded to a monocyclic (see, for example, FIGURE 1) or polycyclic aromatic (see, for example, FIGURES 3, 5, and 10-14). The boron centers can be bonded to the same ring of a polycyclic aromatic (see, for example, FIGURES 5 and 10-13). Alternatively, the boron centers can be bonded to different rings of a polycyclic aromatic (see, for example, FIGURES 3 and 14). In addition to monocyclic and polycyclic aromatic compounds, suitable backbone structures also include compounds having two aromatic rings (see, for example, FIGURES 4, 6-9, and 15). For these compounds, one boron center is bonded to a carbon atom of one aromatic ring and the second boron center is bonded to a carbon atom of a second aromatic ring.

The syntheses of Compounds I and II are illustrated in FIGURE 2. By appropriate selection of the starting material (e.g., $\text{C}_6\text{F}_4\text{X}_2$ in FIGURE 2), a variety of diborane and diborole compounds (e.g., the compounds illustrated in FIGURES 3-15) can be similarly prepared. In the synthetic method, an appropriate starting material (e.g., dihalo or hydrogen substituted aryl compound) is converted to a *bis*-boronic acid. The *bis*-boronic acid is then converted to the dipotassium salt of the *bis*-trifluoroborate. Sequential treatment with boron trifluoride (BF_3) and then boron tribromide (BBr_3) converts the *bis*-trifluoroborate into a *bis*-dibromoboryl compound, from which the final compounds can be prepared. The *bis*-dibromoboryl compound can be treated with the 9-(dimethyltin)perfluorofluorene to provide the corresponding 9-borafluorenyl compounds (i.e., diborole compounds). Alternatively, the *bis*-dibromoboryl compound can be treated with an appropriate organometallic reagent (e.g., di(perfluorophenyl) zinc) to provide the corresponding diboranes. Thus, a general synthetic methodology is provided for aryl compounds substituted with either two borole centers (i.e., aryl diborole) or two borane centers (i.e., aryl diborane).

In order to demonstrate the practice of the current invention, the following examples are presented.

Examples

All glassware was silanized with either Me_2SiCl_2 or Aquaphobe® and then dried in vacuo prior to use. Hexane, toluene and CH_2Cl_2 were pre-purified by passage through columns of activated A-2 alumina and Q-5 deoxo catalyst. Hexane and toluene were further distilled from potassium and sodium metal, respectively and stored over activated 4 Å molecular sieves. Nitrogen gas was dried by passing it through a column packed with a 1:1 v:v mixture of activated 3 Å molecular sieves and BASF R3-11 catalyst followed by a second column packed with alternating layers of 3 Å mol. sieves and SicaPent® indicator. IB gas was purified by passage through a column of 3 Å mol. sieves and BASF R3-11 catalyst prior to use. Bis(borane) 1- F_4 was prepared using modifications to the literature procedure and purified by recrystallization from toluene and hexane. Cumyl chloride (CuCl) was prepared by hydrochlorination of α -methylstyrene and degassed prior to use. 2,6-di-*t*-butyl-4-methylpyridine (DTBMP) was obtained from commercial sources and dried by azeotropic distillation of a toluene solution prior to use. Tris(perfluoro-phenyl)borane was obtained from commercial sources, purified by recrystallization from hexane solution, and was dried by storage of a toluene solution over activated 4 Å mol. sieves. Tris(perfluorophenyl)mercury was prepared by decarboxylation of mercury perfluorophthalate as described in P. Sartori et al. *Chem. Ber.* **1968**, *101*, 2004-9 while bis(perfluorophenyl)zinc was prepared by decarboxylation of zinc perfluorobenzoate as described in P. Sartori et al. *Chem. Ber.* **1967**, *100*, 3016-23. Bis(borane) *o*- $\text{C}_6\text{F}_4[\text{B}(\text{C}_6\text{F}_5)_2]_2$ (1- F_4) was prepared with modifications to the literature method (Williams et al. *J. Am. Chem. Soc.* **1999**, *121*, 3244-3245) and purified by recrystallization from toluene and hexane. Triphenylmethyl tetrakis(perfluorophenyl)borate was prepared from the corresponding lithium salt and triphenylmethyl chloride and purified as described in the literature (Chien, J. C. W.; Tsai, W. M.; Rausch, M. D. *J. Am. Chem. Soc.* **1991**, *113*, 8570-1). Lithium tetrakis(perfluorophenyl)borate was purchased from commercial sources and used without purification while $[(\text{Et}_2\text{O})_2\text{H}][\text{B}(\text{C}_6\text{F}_5)_4]$ was prepared from $[\text{Li}][\text{B}(\text{C}_6\text{F}_5)_4]$ as described in Jutzi, P.; Mueller, C.; Stammli, A.; Stammli, H.-G. *Organometallics* **2000**, *19*, 1442-1444.

Dodecyltrimethylammonium bromide and sodium dodecyl sulfate were obtained from commercial sources and used without purification. Dodecyltrimethylammonium triflate and tetrafluoroborate were prepared from the bromide on treatment with an aqueous solution of silver triflate or silver tetrafluoroborate, respectively. A stock solution of LiCl (121.4 g, 2.86 mole) and NaCl

(6.33 g, 0.108 mole) in H₂O (400 g, 22.20 mole) (hereinafter referred to as anti-freeze solution) (Akopov, E.; *Ah. Prikl. Kim.* **1963**, *36*, 1916-1919) was prepared and was used for most of the polymerization experiments in aqueous suspension or emulsion summarized below. In selected cases, 38 wt % aqueous sulfuric acid or 48 wt% aqueous fluoroboric acid were used instead of anti-freeze solution.

Synthesis of 1,2-Bis(dibromoboryl)tetrafluorobenzene

To a 100 mL round bottom single neck flask containing a magnetic stir bar was charged 2.08 g (1.99×10^{-3} mol) tris(perfluoro-*o*-phenylenemercury) inside a glove box. The flask was next fitted with an air-free style adapter featuring 24/40 outer and inner members connected via an in-line PTFE vacuum stopcock and subsequently attached to a vacuum line with traps pre-charged with 5 wt % KOH in isopropanol. Next, 50 mL dry benzene followed by 12.0 g (4.77×10^{-2} mol) BBr₃ were vacuum transferred to the flask containing the tris(perfluoro-*o*-phenylenemercury). The reaction mixture was then stirred for 24 hours at room temperature under vacuum and then brought into the glove box. Next, the reaction mixture was directly filtered into a tared Carius tube through a frit attached to the 24/40 neck of an air-free style adapter sealed to the Carius tube. The Carius tube was then affixed to the vacuum line and its contents were placed under dynamic vacuum to effect removal of volatiles. This resulted in the production of 2.63 g (90 % yield) of a light brown crystalline product. ¹⁹F NMR spectroscopy showed this material to be > 95% pure. ¹⁹F NMR (benzene-d₆, 300K, 300 MHz): δ -126.21 (d, 2F, *o*-C₆F₅), -147.79 (d, 2F, *m*-C₆F₄).

Synthesis of 1,2-Bis[bis(pentafluorophenyl)boryl]tetrafluorobenzene

To the Carius tube containing 2.63 g (5.38×10^{-3} mol) 1,2-Bis(dibromoboryl)tetrafluorobenzene was added 4.50g (1.13×10^{-2} mol) bis(pentafluorophenyl)zinc and 75 mL dried toluene inside a glove box resulting in the production of a chartreuse colored reaction mixture and the production of a grey precipitate. The tube was then affixed to a vacuum line and subjected to three consecutive freeze/pump/thaw cycles after which the contents were heated to 111 °C for 12 hours. The cooled reaction mixture was then filtered into a 250 mL single neck round bottom flask fitted with a filter frit inside the glove box after which the frit was replaced with an adjustable 24/40 gas inlet adapter. The flask was then connected to a Schlenk line and placed under dynamic vacuum to affect

removal of the volatiles to yield a lightly yellow solid. This material was then recrystallized several times from a 60/40 vol/vol mixture of toluene and hexane to give 4.01 g (89 %) white crystals. ^{19}F NMR spectroscopy showed this material to be > 99% pure. ^{19}F NMR (CDCl_3 , 300K, 282 MHz) δ - 124.41 (d, 2F, *o*- C_6F_4), - 126.0 (d, 8F, *o*- C_6F_5), -141.30 (t, 4F, *p*- C_6F_5), -147.74 (d, 2F, *m*- C_6F_4), -160.26 (m, 8F, *m*- C_6F_5).

Polymerization Examples

Example 1 – Polymerization of IB in Liquid Monomer

IB was condensed at -78°C into a graduated cylinder under N_2 on a vacuum line. Twelve mL was then vacuum transferred into a rb flask containing about 1 g of tri-*n*-octylaluminum. After stirring for 30 min at -78°C , the monomer was vacuum transferred to a second rb flask equipped with a septum inlet. A toluene solution of **1-F₄** (0.048 mL of 0.05 M solution, final concentration 0.20 mM) was added to the rapidly stirred monomer via gas-tight syringe at -78°C . An uncontrolled, exothermic polymerization occurred which was accompanied by rapid gelation of the solution and cessation of stirring. After quenching with 1 mL 0.2M NaOCH_3 in methanol, all volatiles were removed and the residue was washed with methanol prior to being taken up in hexane. The resultant polymer solution was filtered, concentrated to dryness, and dried in a vacuum oven at 30 in Hg at 90°C for 24 h. Yield and characterization data are summarized in the Table. Under the same conditions, but in the presence of 2-20 mM DTBP, little to no PIB is formed thus implicating initiation by protic impurities.

Example 2 – Co-polymerization of IB with Isoprene in Liquefied Monomer

IB was condensed at -78°C into a graduated cylinder under N_2 on a vacuum line. About 12 mL was then vacuum transferred into a rb flask containing about 1 g of tri-*n*-octylaluminum and 0.18 mL of isoprene. After stirring for 30 min at -78°C , the monomer and isoprene were vacuum transferred to a second rb flask equipped with a septum inlet. A toluene solution of **1-F₄** (0.048 mL of 0.05 M solution, final concentration 0.20 mM) was added to the rapidly stirred monomer solution via gas-tight syringe. An uncontrolled, violently exothermic polymerization occurred which was accompanied by rapid gelation of the solution and cessation of stirring. The polymerization was halted as described in Example 1 after one hour at -78°C . Polymer was isolated as described in Example 1

and 6.67 g of butyl rubber (76% conversion) was obtained with $M_w = 71.1$ K and $M_w/M_n = 2.08$. A ^1H NMR spectrum of this material revealed the presence of about 2 mol% trans-1,4-isoprene units.

Examples 3-5 – Polymerization of IB in Hexane Solution

IB was condensed at -78°C into a graduated cylinder under N_2 on a vacuum line. About five mL was then vacuum transferred into a rb flask containing about 1g of tri-n-octylaluminum and 19 mL of hexane. After stirring for 30 min at -78°C , the monomer and solvent were vacuum transferred to a second rb flask equipped with a septum inlet. A toluene solution of 1-F_4 (0.766 mL of 0.065 M solution, final concentration 2.0 mM) was added to the rapidly stirred monomer solution via gas-tight syringe. A controlled polymerization occurred which was quenched as described in Example 1 after one hour at -78°C . Polymer was isolated as described in Example 1 and results are summarized in the Table.

Example 6 – Polymerization of IB in Hexane Solution in the Presence of Low Concentrations of 1-F_4

IB was condensed at -78°C into a graduated cylinder under N_2 on a vacuum line. About five mL was then vacuum transferred into a rb flask containing about 1g of tri-n-octylaluminum and 19 mL of hexane. After stirring for 30 min at -78°C , the monomer and solvent were vacuum transferred to a second rb flask equipped with a septum inlet. A toluene solution of 1-F_4 (0.766 mL of 0.065 mM solution, final concentration 2.0×10^{-6} M) was added to the rapidly stirred monomer solution via gas-tight syringe. A controlled polymerization occurred which was quenched as described in Example 1 after one hour at -78°C . Polymer was isolated as described in Example 1 to provide 117 mg of PIB (3.0% conversion) with $M_w = 483$ K and $M_w/M_n = 1.90$.

In a separate experiment, a solution of IB and hexane of the same composition and prepared in the same manner was titrated with a stock solution of benzophenone ketyl in xylenes/tetraglyme to a pale blue end point. In this manner the concentration of dissolved water was estimated to be 2.5×10^{-5} M or roughly $10 \times$ higher than the amount of 1-F_4 used in the above experiment.

Comparative Example 1

Using the procedure summarized in Examples 2-4, a toluene solution of $B(C_6F_5)_3$ (0.80 mL of 0.126 M, final concentration 4.0 mM) was added to a hexane solution of IB. After 1 hour at -78°C , work-up as described above provided trace quantities of PIB; properties are summarized in the Table.

Examples 7-10 – Polymerization of IB in Hexane Solution in the presence of CumCl and DTBP

The procedure of examples 2-4 was followed. Prior to the addition of $1-F_4$, a hexane solution of DTBP (1.0 mL of 0.5 M) and cumyl chloride (0.172 mL of 0.029 M in CH_2Cl_2) were added to a solution of IB in hexane at -78°C , followed by the addition of $1-F_4$ as described in Example 2. A controlled polymerization occurred which was worked up after 1 h as in Example 1 and the results are summarized in the Table.

Comparative Example 2

Using the procedure summarized in Examples 5-8, a toluene solution of $B(C_6F_5)_3$ (0.80 mL of 0.126 M, final concentration 4.0 mM) was added to a solution of IB, cumyl chloride and DTBP in hexane. After 1 hour at -78°C , work-up as described above failed to provide detectable quantities of PIB.

Table - Polymerization of i-Butene in Hexane Solution at -78°C

Example	$1-F_4$ (mM)	CumCl (mM)	IB (M)	DTBP (mM)	M_w (K)	PDI	Yield (%)
1	0.20	0	14.6 ^a	0	69.0	3.16	100
3	0.64	0	0.56	0	97.8	2.22	100
4	2.00	0	3.3	0	195	3.18	100
5	2.00	0	3.3	0	258	2.38	100
$B(C_6F_5)_3$ (4 mM)	0	0	3.3	0	96.8	1.75	0.10
7	2.00	0.20	2.8	20	393	2.06	22
8	2.00	0.30	2.8	20	255	1.92	21
9	2.00	0.20	2.8	2	779	2.11	93
10	2.00	0.20	3.3	20	361	1.72	42
$B(C_6F_5)_3$ (4 mM)	0	0.20	3.3	20	-	-	0

a. Liquid i-butene.

Example 10 – Polymerization of IB in Aqueous Suspension

Eighteen mL of anti-freeze solution was added to a 3 neck rb flask equipped with an over-head mechanical stirrer. Isobutene (18 mL) was condensed at -60°C into this flask under static vacuum. The mixture was stirred at 550 rpm under N_2 while adding 10.0 mL of a solution of **1-F₄** in hexane (1.19 mM) over a period of 5 min by syringe. During this period the mixture turned milky white in appearance. After 1 h at -60°C , the mixture was allowed to warm to 25°C while venting the flask to the air. The mixture was diluted with water (100 mL) and CH_2Cl_2 (50 mL) and transferred to a separatory funnel. The aqueous phase was extracted with CH_2Cl_2 (2 ' 50 mL) and the organic extracts were dried over MgSO_4 , filtered washing with additional CH_2Cl_2 and concentrated to dryness in vacuo. Poly(isobutene) (6.10 g, 48% conversion) was obtained with $M_w = 66.1 \text{ K}$ and $M_w/M_n = 2.55$.

Example 11 – Polymerization of IB in Aqueous Suspension in the Presence of a Polar Solvent

Eighteen mL of anti-freeze solution and 9.0 mL of CH_2Cl_2 were added to a 3 neck rb flask equipped with an over-head mechanical stirrer. Isobutene (9.0 mL) was condensed at -60°C into this flask under static vacuum. The mixture was stirred at 550 rpm under N_2 while adding 10.0 mL of a solution of **1-F₄** in hexane (1.19 mM) over a period of 5 min by syringe. During this period the mixture turned milky white in appearance. After 1 h at -60°C , the mixture was allowed to warm to 25°C while venting the flask to the air. The mixture was diluted with water (100 mL) and CH_2Cl_2 (50 mL) and transferred to a separatory funnel. The aqueous phase was extracted with CH_2Cl_2 (2 ' 50 mL) and the organic extracts were dried over MgSO_4 , filtered washing with additional CH_2Cl_2 and concentrated to dryness in vacuo. Poly(isobutene) (2.05 g, 32% conversion) was obtained with $M_w = 121 \text{ K}$ and $M_w/M_n = 1.96$.

Example 12 – Polymerization of IB in Aqueous Suspension

Eighteen mL of anti-freeze solution were added to a 3 neck rb flask equipped with an over-head mechanical stirrer. Isobutene (18.0 mL) was condensed at -60°C into this flask under static vacuum. The mixture was stirred at 550 rpm under N_2 while adding 1.00 mL of a solution of 1-F₄ in toluene (11.9 mM) over a period of 5 sec by syringe. During the addition of 1-F₄ the charge turned yellow and remained so for 10 sec before finally becoming milky white in appearance. The reaction was vigorously exothermic as witnessed by refluxing of the monomer. After 1 h at -60°C , the mixture was allowed to warm to 25°C while venting the flask to the air. The mixture was diluted with water (100 mL) and CH_2Cl_2 (50 mL) and transferred to a separatory funnel. The aqueous phase was extracted with CH_2Cl_2 (2 ' 50 mL) and the organic extracts were dried over MgSO_4 , filtered washing with additional CH_2Cl_2 and concentrated to dryness in vacuo. Poly(isobutene) (4.95 g, 39 % conversion) was obtained with $M_w = 23.9 \text{ K}$ and $M_w/M_n = 2.38$.

Example 13 – Polymerization of IB in Aqueous Emulsion

Eighteen mL of anti-freeze solution and 0.100 g of dodecyltrimethylammonium bromide were added to a 3 neck rb flask equipped with an over-head mechanical stirrer. Isobutene (18.0 mL) was condensed at -60°C into this flask under static vacuum. The mixture was stirred at 550 rpm under N_2 while adding 1.00 mL of a solution of 1-F₄ in hexane (11.9 mM) over a period of 5 sec by syringe. The reaction was vigorously exothermic as witnessed by refluxing of the monomer. After 1 h at -60°C , the mixture was allowed to warm to 25°C while venting the flask to the air. The mixture was diluted with water and methanol (100 mL of 1:1 v:v) to break the emulsion and CH_2Cl_2 (50 mL) and transferred to a separatory funnel. The aqueous phase was extracted with CH_2Cl_2 (2 ' 50 mL) and the organic extracts were dried over MgSO_4 , filtered washing with additional CH_2Cl_2 and concentrated to dryness in vacuo. Poly(isobutene) (595 mg, 4.7% conversion) was obtained with $M_w = 57.2 \text{ K}$ and $M_w/M_n = 2.74$.

Example 14 – Polymerization of IB in Aqueous Emulsion

Eighteen mL of anti-freeze solution and 0.100 g of sodium dodecyl sulfate (SDS) were added to a 3 neck rb flask equipped with an over-head mechanical stirrer. Isobutene (18.0 mL) was condensed at -60°C into this flask under static vacuum. The mixture was stirred at 550 rpm under N_2 while adding 1.00 mL of a solution of 1- F_4 in toluene (11.9 mM) over a period of 5 sec by syringe. During the addition of 1- F_4 the charge turned yellow and remained so for 10 sec before finally becoming milky white in appearance. The reaction was vigorously exothermic as witnessed by refluxing of the monomer. After 1 h at -60°C , the mixture was allowed to warm to 25°C while venting the flask to the air. The mixture was diluted with water and methanol (100 mL of 1:1 v:v) to break the emulsion and CH_2Cl_2 (50 mL) and transferred to a separatory funnel. The aqueous phase was extracted with CH_2Cl_2 (2 \times 50 mL) and the organic extracts were dried over MgSO_4 , filtered washing with additional CH_2Cl_2 and concentrated to dryness in vacuo. Poly(isobutene) (4.10 g, 32 % conversion) was obtained with $M_w = 25.4 \text{ K}$ and $M_w/M_n = 2.37$.

Example 15 – Copolymerization of IB and Isoprene in Aqueous Suspension

Eighteen mL of anti-freeze solution and 2.0 mL of isoprene were added to a 3 neck rb flask equipped with an over-head mechanical stirrer. Isobutene (18.0 mL) was condensed at -60°C into this flask under static vacuum. The mixture was stirred at 550 rpm under N_2 while adding 1.00 mL of a solution of 1- F_4 in toluene (11.9 mM) over a period of 5 sec by syringe. During the addition of 1- F_4 the charge turned yellow and remained so for 20 sec before finally becoming milky white in appearance. The reaction was vigorously exothermic as witnessed by refluxing of the monomer. After 1 h at -60°C , the mixture was allowed to warm to 25°C while venting the flask to the air. The mixture was diluted with water (100 mL) and CH_2Cl_2 (50 mL) and transferred to a separatory funnel. The aqueous phase was extracted with CH_2Cl_2 (2 \times 50 mL) and the organic extracts were dried over MgSO_4 , filtered washing with additional CH_2Cl_2 and concentrated to dryness in vacuo. Butyl rubber (3.35 g, 24 % conversion) was obtained with $M_w = 86.2 \text{ K}$ and $M_w/M_n = 2.89$. A ^1H NMR spectrum revealed the presence of ca. 5 mol% trans-1,4-isoprene units.

Example 16 – Copolymerization of IB and Isoprene in Aqueous Emulsion

Eighteen mL of anti-freeze solution, 2.0 mL of isoprene, and 0.100 g of SDS were added to a 3 neck rb flask equipped with an over-head mechanical stirrer. Isobutene (18.0 mL) was condensed at -60°C into this flask under static vacuum. The mixture was stirred at 550 rpm under N_2 while adding 1.00 mL of a solution of 1- F_4 in toluene (11.9 mM) over a period of 5 sec by syringe. During the addition of 1- F_4 the charge turned yellow and remained so for 20 sec before finally becoming milky white in appearance. The reaction was vigorously exothermic as witnessed by refluxing of the monomer. After 1 h at -60°C , the mixture was allowed to warm to 25°C while venting the flask to the air. The mixture was diluted with water and methanol (100 mL of 1:1 v:v) to break the emulsion and CH_2Cl_2 (50 mL) and transferred to a separatory funnel. The aqueous phase was extracted with CH_2Cl_2 (2 \times 50 mL) and the organic extracts were dried over MgSO_4 , filtered washing with additional CH_2Cl_2 and concentrated to dryness in vacuo. Butyl rubber (2.49 g, 18% conversion) was obtained with $M_w = 77.3 \text{ K}$ and $M_w/M_n = 2.75$. A ^1H NMR spectrum revealed the presence of ca. 5 mol% trans-1,4-isoprene units.

Example 17 – Polymerization of IB in Aqueous Sulfuric Acid Suspension

Eighteen mL of 38 wt% sulfuric acid solution were added to a 3 neck rb flask equipped with an over-head mechanical stirrer. Isobutene (18.0 mL) was condensed at -60°C into this flask under static vacuum. The mixture was stirred at 550 rpm under N_2 while adding 1.00 mL of a solution of 1- F_4 in toluene (11.9 mM) over a period of 5 sec by syringe. During the addition of 1- F_4 the charge turned yellow and remained so for 10 sec before finally becoming milky white in appearance. The reaction was vigorously exothermic as witnessed by refluxing of the monomer. After 1 h at -60°C , the mixture was allowed to warm to 25°C while venting the flask to the air. The mixture was diluted with water (100 mL) and CH_2Cl_2 (50 mL) and transferred to a separatory funnel. The aqueous phase was extracted with CH_2Cl_2 (2 \times 50 mL) and the organic extracts were dried over MgSO_4 , filtered washing with additional CH_2Cl_2 and concentrated to dryness in vacuo. Poly(isobutene) (3.67 g, 29 % conversion) was obtained with $M_w = 38.4 \text{ K}$ and $M_w/M_n = 2.05$.

Example 18 – Polymerization of IB in Aqueous Sulfuric Acid Emulsion

Eighteen mL of 38 wt% sulfuric acid solution and 0.100 g of dodecyltrimethylammonium triflate were added to a 3 neck rb flask equipped with an over-head mechanical stirrer. Isobutene (18.0 mL) was condensed at -60°C into this flask under static vacuum. The mixture was stirred at 550 rpm under N_2 while adding 1.00 mL of a solution of 1- F_4 in toluene (11.9 mM) over a period of 5 sec by syringe. During the addition of 1- F_4 the charge turned yellow and remained so for 10 sec before finally becoming milky white in appearance. The reaction was vigorously exothermic as witnessed by refluxing of the monomer. After 1 h at -60°C , the mixture was allowed to warm to 25°C while venting the flask to the air. The mixture was diluted with water and methanol (100 mL of 1:1 v:v) to break the emulsion and CH_2Cl_2 (50 mL) and transferred to a separatory funnel. The aqueous phase was extracted with CH_2Cl_2 (2 ' 50 mL) and the organic extracts were dried over MgSO_4 , filtered washing with additional CH_2Cl_2 and concentrated to dryness in vacuo. Poly(isobutene) (1.82 g, 14 % conversion) was obtained with $M_w = 55.7 \text{ K}$ and $M_w/M_n = 2.82$.

Example 19 – Polymerization of IB in Aqueous Fluoroboric Acid Suspension

Eighteen mL of 48 wt% fluoroboric acid solution were added to a 3 neck rb flask equipped with an over-head mechanical stirrer. Isobutene (18.0 mL) was condensed at -80°C into this flask under static vacuum. The mixture was stirred at 550 rpm under N_2 while adding 1.00 mL of a solution of 1- F_4 in toluene (11.9 mM) over a period of 5 sec by syringe. During the addition of 1- F_4 the charge turned yellow and remained so during the entire course of the polymerization although the intensity of the color gradually decreased with increasing time. The reaction was vigorously exothermic as witnessed by refluxing of the monomer. After 1 h at -80°C , the mixture was allowed to warm to 25°C while venting the flask to the air. The mixture was diluted with water (100 mL) and CH_2Cl_2 (50 mL) and transferred to a separatory funnel. The aqueous phase was extracted with CH_2Cl_2 (2 ' 50 mL) and the organic extracts were dried over MgSO_4 , filtered washing with additional CH_2Cl_2 and concentrated to dryness in vacuo. Poly(isobutene) (7.28 g, 58 % conversion) was obtained with $M_w = 50.8 \text{ K}$ and $M_w/M_n = 2.36$.

Example 20 – Polymerization of IB in Aqueous Fluoroboric Acid Emulsion

Eighteen mL of 48 wt% fluoroboric acid solution and 0.100 g of dodecyltrimethylammonium tetrafluoroborate were added to a 3 neck rb flask equipped with an over-head mechanical stirrer. Isobutene (18.0 mL) was condensed at $-80\text{ }^{\circ}\text{C}$ into this flask under static vacuum. The mixture was stirred at 550 rpm under N_2 while adding 1.00 mL of a solution of 1-F₄ in toluene (11.9 mM) over a period of 5 sec by syringe. During the addition of 1-F₄ the charge turned yellow and remained so for 10 min before finally becoming milky white in appearance. The reaction was vigorously exothermic as witnessed by refluxing of the monomer. After 1 h at $-80\text{ }^{\circ}\text{C}$, the mixture was allowed to warm to $25\text{ }^{\circ}\text{C}$ while venting the flask to the air. The mixture was diluted with water and methanol (100 mL of 1:1 v:v) to break the emulsion and CH_2Cl_2 (50 mL) and transferred to a separatory funnel. The aqueous phase was extracted with CH_2Cl_2 (2 × 50 mL) and the organic extracts were dried over MgSO_4 , filtered washing with additional CH_2Cl_2 and concentrated to dryness in vacuo. Poly(isobutene) (6.57 g, 52 % conversion) was obtained with $M_w = 39.9\text{ K}$ and $M_w/M_n = 2.12$.

Example 21 – Copolymerization of IB and Isoprene in Aqueous Fluoroboric Acid Emulsion

Eighteen mL of 48 wt% fluoroboric acid solution, 8.0 mL hexane, 0.100 g of dodecyltrimethylammonium tetrafluoroborate, and 1.0 mL of isoprene were added to a 3 neck rb flask equipped with an over-head mechanical stirrer. Isobutene (9.0 mL) was condensed at $-80\text{ }^{\circ}\text{C}$ into this flask under static vacuum. The mixture was stirred at 550 rpm under N_2 while adding 1.00 mL of a solution of 1-F₄ in toluene (11.9 mM) over a period of 5 sec by syringe. During the addition of 1-F₄ the charge turned yellow and remained so during the entire course of the polymerization although the intensity of the color gradually decreased with increasing time. The reaction was vigorously exothermic as witnessed by refluxing of the monomer. After 1 h at $-80\text{ }^{\circ}\text{C}$, the mixture was allowed to warm to $25\text{ }^{\circ}\text{C}$ while venting the flask to the air. The mixture was diluted with water (100 mL) and CH_2Cl_2 (50 mL) and transferred to a separatory funnel. The aqueous phase was extracted with CH_2Cl_2 (2 × 50 mL) and the organic extracts were dried over MgSO_4 , filtered washing with additional CH_2Cl_2 and concentrated to dryness in vacuo. Butyl rubber (2.76 g, 39 % conversion) was obtained with $M_w = 80.9\text{ K}$ and $M_w/M_n = 2.90$. A ^1H NMR spectrum revealed the presence of ca. 14 mol% trans-1,4-isoprene units.

Example 22 – Copolymerization of IB and Isoprene in Aqueous Fluoroboric Acid Suspension

Eighteen mL of 48 wt% fluoroboric acid solution, 8.0 mL hexane, and 1.0 mL of isoprene were added to a 3 neck rb flask equipped with an over-head mechanical stirrer. Isobutene (9.0 mL) was condensed at -80°C into this flask under static vacuum. The mixture was stirred at 550 rpm under N_2 while adding 1.00 mL of a solution of 1- F_4 in toluene (11.9 mM) over a period of 5 sec by syringe. During the addition of 1- F_4 the charge turned yellow and remained so for 10 min before finally becoming milky white in appearance. The reaction was vigorously exothermic as witnessed by refluxing of the monomer. After 1 h at -80°C , the mixture was allowed to warm to 25°C while venting the flask to the air. The mixture was diluted with water and methanol (100 mL of 1:1 v:v) to break the emulsion and CH_2Cl_2 (50 mL) and transferred to a separatory funnel. The aqueous phase was extracted with CH_2Cl_2 (2 ' 50 mL) and the organic extracts were dried over MgSO_4 , filtered washing with additional CH_2Cl_2 and concentrated to dryness in vacuo. Butyl rubber (2.67 g, 38 % conversion) was obtained with $M_w = 106\text{ K}$ and $M_w/M_n = 1.91$. A ^1H NMR spectrum revealed the presence of ca. 15 mol% trans-1,4-isoprene units.

Example 23 – Polymerization of IB in Aqueous Suspension Coinitiated by 1,2- $\text{C}_6\text{F}_4(9\text{-BC}_{12}\text{F}_8)_2$

Eighteen mL of anti-freeze solution were added to a 3 neck rb flask equipped with an over-head mechanical stirrer. Isobutene (18.0 mL) was condensed at -60°C into this flask under static vacuum. The mixture was stirred at 550 rpm under N_2 while adding 1.00 mL of a solution of 1,2- $\text{C}_6\text{F}_4(9\text{-BC}_{12}\text{F}_8)_2$ in toluene (11.9 mM) over a period of 5 sec by syringe. During the addition of this solution the charge turned yellow and remained so for 10 sec before finally becoming milky white in appearance. The reaction was vigorously exothermic as witnessed by refluxing of the monomer. After 1 h at -60°C , the mixture was allowed to warm to 25°C while venting the flask to the air. The mixture was diluted with water (100 mL) and CH_2Cl_2 (50 mL) and transferred to a separatory funnel. The aqueous phase was extracted with CH_2Cl_2 (2 ' 50 mL) and the organic extracts were dried over MgSO_4 , filtered washing with additional CH_2Cl_2 and concentrated to dryness in vacuo. Poly(isobutene) (5.04 g, 40 % conversion) was obtained with $M_w = 89.6\text{ K}$ and $M_w/M_n = 3.83$.

Example 24 – Polymerization of IB in Aqueous HCl Suspension

Eighteen mL of 12 N HCl (aq) were added to a 3 neck rb flask equipped with an overhead mechanical stirrer. Isobutene (18.0 mL) was condensed at -25°C into this flask under static vacuum. The mixture was stirred at 550 rpm under N_2 while adding 1.00 mL of a solution of 1- F_4 in toluene (11.9 mM) over a period of 5 sec by syringe. The reaction was vigorously exothermic as witnessed by refluxing of the monomer. After 1 h at -25°C , the mixture was allowed to warm to 25°C while venting the flask to the air. The mixture was diluted with water (100 mL) and CH_2Cl_2 (50 mL) and transferred to a separatory funnel. The aqueous phase was extracted with CH_2Cl_2 (2 \times 50 mL) and the organic extracts were dried over MgSO_4 , filtered washing with additional CH_2Cl_2 and concentrated to dryness in vacuo. Poly(isobutene) (1.96 g, 16 % conversion) was obtained with $M_w = 20.3 \text{ K}$ and $M_w/M_n = 1.88$.

Comparative Example 3

Using the procedure summarized in Example 10, 10.0 mL of a hexane: CH_2Cl_2 (60:40 v:v) solution of $[\text{Ph}_3\text{C}][\text{B}(\text{C}_6\text{F}_5)_4]$ (2.4 mM) was added to 18.0 mL of IB and 18.0 mL of anti-freeze solution at -60°C . On addition the mixture turned yellow in color. After 1 hour work-up as described above provided no poly(isobutene).

Comparative Example 4

Using the procedure summarized in Example 10, a hexane solution of $\text{B}(\text{C}_6\text{F}_5)_3$ (10.0 mL of 2.4 mM) was added to 18.0 mL of IB and 18.0 mL of anti-freeze solution at -60°C . After 1 hour, work-up as described above failed to provide detectable quantities of polymer.

Comparative Example 5

Using the procedure summarized in Example 12, 18.0 mL of IB was condensed into a solution of 0.020 g (2.39×10^{-5} moles) $[\text{Li}][\text{B}(\text{C}_6\text{F}_5)_4]$ in 18.0 mL of anti-freeze solution. The flask contents were then stirred under N_2 at -60°C at 550 rpm. Polymerization was allowed to continue for a full hour before warming the reactor contents to room temperature by diluting the reactor contents with additional water and CH_2Cl_2 . During this period, large amounts of gas evolved. Organics were

then extracted with CH_2Cl_2 and dried over MgSO_4 before isolating solids by removal of volatiles under reduced pressure. No PIB was isolated and the addition of 18.0 mL of CH_2Cl_2 to increase the solubility of this salt in the organic phase did not affect the outcome.

5 Comparative Example 6

Using the procedure summarized in Example 12, 1.0 mL of a toluene solution of $[(\text{Et}_2\text{O})_2\text{H}][\text{B}(\text{C}_6\text{F}_5)_4]$ (12 mM) was to 18.0 mL of IB and 18.0 mL of anti-freeze solution at -60°C . After 1 hour work-up as described above provided no poly(isobutene).

10 Comparative Example 7

Using the procedure summarized in Example 12, 1.0 mL of a toluene solution of 9,10- $(\text{C}_6\text{F}_5\text{B})_2\text{C}_{12}\text{F}_8$ (compound 2, 10 mM) was added to 18.0 mL of IB and 18.0 mL of anti-freeze solution at -60°C . After 1 hour work-up as described above provided no poly(isobutene).

15 Example 25 - Synthesis of 1,2-bis-(9-Bora-1,2,3,4,5,6,7,8-octafluorofluorenyl)-3,4,5,6-tetrafluorobenzene: 1,2-[B(C₁₂F₈)]₂C₆F₄

General Considerations. NMR spectra were measured on a Bruker Avance DRX-400 (^{11}B at 128.41 MHz) and a Bruker AMX2-300 (^{19}F at 282.41 MHz). ^{11}B NMR spectra were referenced relative to $\text{BF}_3\cdot\text{Et}_2\text{O}$ at 0 ppm. ^{19}F NMR spectra were referenced externally to C_6F_6 at -163 ppm relative to CFCl_3 at 0 ppm. 1,2-Dibromotetrafluorobenzene (Aldrich), 1.6 M BuLi (Aldrich), KHF_2 (Aldrich), and BF_3 (Aldrich) were used as supplied. $\text{B}(\text{OCH}_3)_3$ (Aldrich) was distilled over Na prior to use and BBr_3 (Aldrich) was distilled from Cu wire prior to use.

All manipulations with aryldihalogenboranes were performed using standard vacuum and Schlenk techniques or in a glovebox under an atmosphere of argon. CH_2Cl_2 was distilled from CaH_2 prior to use. CD_2Cl_2 and C_6D_6 were purchased from Cambridge Isotopes and rigorously dried then distilled from CaH_2 and Na/benzophenone respectively. CD_3CN and D_2O were purchased from Cambridge Isotopes and Aldrich, respectively, and used as is.

The synthesis of 1,2-bis-(9-bora-1,2,3,4,5,6,7,8-octafluorofluorenyl)-3,4,5,6-tetrafluorobenzene described below is schematically illustrated in FIGURE 2.

Synthesis of 1,2-bis-[(Dihydroxy)boryl]tetrafluorobenzene (1). Butyllithium (1.6 M in hexanes, 12.6 mL, 20.16 mmol) was added dropwise to a stirred solution of 1,2-dibromotetrafluorobenzene (2.6 g, 8.44 mmol) in ether (50 mL) at -78°C. After 2 hours this solution was slowly added to a pre-cooled solution (-78°C) of trimethylborate (2.3 mL, 20.52 mmol) in ether (25 mL). The resulting suspension was stirred at -78°C for two hours then gradually warmed to room temperature and hydrolyzed with 20 mL of 10% HCl. The yellow organic phase was separated and the aqueous phase was extracted with dichloromethane (3 x 15 mL). The combined organic phases were washed with water (3 x 10 mL) and dried over magnesium sulfate. Removal of solvent under reduced pressure gave a yellow oil that was recrystallized from water at a pH of 4 to afford a crystalline solid. (1.5 g, 75%) ¹⁹F NMR (D₂O/HCl) δ: -136.6 (d, J_{F-F} = 28.3 Hz, 2F, C₆F₄), -156.5 (d, J_{F-F} = 28.3 Hz, 2F, C₆F₄). ¹¹B NMR (D₂O/HCl) δ: 16.9 (br).

Synthesis of Potassium Tetrafluorophenyl-bis-1,2-trifluoroborate (2). A solution of the bis-boronic acid 1 (2.4 g, 10.11 mmol) in methanol (20 mL) was added to a stirred solution of potassium hydrogenfluoride (5.5 g, 70.41 mmol) in water (40 mL) and stirred for 1 hour. The solution was filtered and the solid was washed with water (3 x 10 mL) then ether (3 x 10 mL) and dried under reduced pressure. The product was recrystallized from hot acetonitrile affording an off-white solid (1.04 g, 28%). ¹⁹F NMR (CD₃CN/D₂O) δ: -139.0 (d, J_{F-F} = 28.2 Hz, 2F, C₆F₄), -144.1 (m, 6F, -BF₃), -160.1 (d, J_{F-F} = 28.2 Hz, 2F, C₆F₄). ¹¹B NMR (CD₃CN/D₂O) δ: 3.9 (multiplet).

Synthesis of 1,2-bis-(Difluoroboryl)tetrafluorobenzene (3). An excess of boron trifluoride gas was introduced to a stirred suspension of the potassium aryltrifluoroborate salt 2 (1.0 g, 27.32 mmol) in dichloromethane in a thick walled bomb at -40°C. After 30 minutes the solution was degassed under vacuum at -78°C. The resultant red colored solution was filtered and the remaining solid was washed with dichloromethane (2 x 5 mL). A deep red liquid was obtained after the solvent was distilled from product under reduced pressure. (0.4 g, 60%). ¹⁹F NMR (CD₂Cl₂) δ: -72.4 (br. s, 4F, -BF₂), -126.9 (m, 2F, C₆F₄), -146.5 (m, 2F, C₆F₄). ¹¹B NMR (CD₂Cl₂) δ: 22.6 (br m).

Synthesis of 1,2-bis-(Dibromoboryl)tetrafluorobenzene (4). Boron tribromide (0.76 g, 3.05 mmol) was introduced to a solution of 3 (0.15 g, 0.61 mmol) in toluene (5 mL) in a thick walled bomb at -78°C. The bomb was sealed and heated at 60°C for 30 minutes. Volatiles were removed

under reduced pressure to afford the desired product. (0.25 g, 85%). ^{19}F NMR (C_6D_6) δ : -125.7 (m, 2F, C_6F_4), -147.3 (m, 2F, C_6F_4). ^{11}B NMR (C_6D_6) δ : 54 (br).

Synthesis of 1,2-bis-[9-Bora-1,2,3,4,5,6,7,8-octafluorofluorenyl]tetrafluorobenzene (Compound I). $\text{C}_{12}\text{F}_8\text{SnMe}_2$ (0.786 g, 1.77 mmol) and $\text{C}_6\text{F}_4(\text{BBr}_2)_2$ (0.435 g, 0.84 mmol) were dissolved in toluene (20 ml), sealed in glass bomb equipped with a Kontes valve and heated to 85°C for 36 hours. The solvent was removed *in vacuo* and the Me_2SnBr_2 by-product was removed via sublimation (30°C , 0.01 mm Hg). The sublimation residues were placed in a frit assembly and hexanes (30 ml) was condensed into the flask. The solution was cooled to -78°C and stirred for 1 hour. The solution was cold filtered and a light yellow solid was obtained and dried *in vacuo*. Yield: 0.520 g, 81.2 %. ^{19}F NMR (C_6D_6): δ -121.1 (br, 4F), -123.6 (aa'bb' pattern, 2F), -128.9 (br, 4F), -138.6 (br, 4F), -148.6 (aa'bb' pattern, 2F), -151.9 (br, 4F). l_{max} (hexanes) 425nm $\epsilon = 5.9 \times 10^2 \text{ L mol}^{-1} \text{ cm}^{-1}$. Anal. Calcd. for $\text{C}_{30}\text{F}_{20}\text{B}_2$: C 47.29. Found: C 47.78.

Example 26 - Synthesis of 1,2-bis-[Di(perfluorophenyl)boryl]-3,4,5,6-tetrafluorobenzene:

1,2-[B(C₆F₅)₂]₂C₆F₄

The synthesis of 1,2-bis-[di(perfluorophenyl)boryl]-3,4,5,6-tetrafluorobenzene (1,2-[B(C₆F₅)₂]₂C₆F₄) (Compound II) described below is schematically illustrated in FIGURE 2.

Compound II was prepared from 1,2-bis-(dibromoboryl)tetrafluorobenzene (4), prepared as described above in Example 1.

Toluene (25 ml) was condensed into an evacuated bomb containing $\text{Zn}(\text{C}_6\text{F}_5)_2$ (1.40 g, 3.50 mmol) at -78°C . To this colorless solution was added boron 1,2-bis-(dibromoboryl)tetrafluorobenzene (0.84 g, 1.73 mmol) as a neat liquid. The mixture was heated at 80°C for 12 hours, after which the toluene was removed under reduced pressure. The white residue was extracted using toluene (40 ml), filtered and concentrated. The product was isolated after crystallization from hot toluene and washing with cold hexanes (0.8 g, 0.95 mmol, 55%). ^{19}F NMR (C_6D_6) δ : -127.6 (m, 2F, C_6F_4); -128.5 (d, 8F, *o*- C_6F_5); -141.6 (m, 2F, C_6F_4); -148.9 (m, 4F, *p*- C_6F_5); -161.5 (m, 8F, *m*- C_6F_5). Anal. Calcd. for $\text{C}_{30}\text{B}_2\text{F}_{24}$: C, 42.9. Found: C, 42.5.

Thus it should be evident that method of the present invention is highly effective in synthesizing polyolefins in the absence of a halogenated solvent. The invention is particularly suited for the synthesis of polyisobutene and butyl rubber, but is necessarily limited thereto. Additionally, the

process exemplified is a suspension polymerization, which facilitates heat and mass transfer. However, solution polymerization in liquid or diluted monomer and a supported catalyst is also envisioned within the present invention. The method of the present invention can be used separately with other methods and the like, as well as for the manufacture of other polyolefin materials.

5 It is, therefore, to be understood that any variations evident fall within the scope of the claimed invention and thus, the selection of specific component elements can be determined without departing from the spirit of the invention herein disclosed and described.